

A New MIMO SAR System based on Alamouti Space-Time Coding Scheme and OFDM-LFM Waveform Design

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ABSTRACT

In recent years, multi-input and multi-output (MIMO) radar has attracted much attention of many researchers and institutions. MIMO radar transmits multiple signals, and receives the backscattered signals reflected from the targets. In contrast with conventional phased array radar and SAR system, MIMO radar system has significant potential advantages for achieving higher system SNR, more accurate parameter estimation, or high resolution of radar image. In this paper, we propose a new MIMO SAR system based on Alamouti space-time coding scheme and orthogonal frequency division multiplexing linearly frequency modulated (OFDM-LFM) for obtaining higher system signal-to-noise ratio (SNR) and better range resolution of SAR image.

Keywords: synthetic aperture radar (SAR), multiple-input and multiple-output (MIMO), Alamouti Scheme, orthogonal frequency division multiplexing (OFDM)

1. INTRODUCTION

Multi-input and multi-output (MIMO) is a highly focused research area in mobile communications. MIMO communication systems can improve link reliability and multiplexing gain. MIMO radar based on the idea of employing multiple transmitters with multiple waveforms and multiple receivers to receive the echoes reflected from targets. Because of multiple transmitters in MIMO system, we have high flexibility of waveform design to achieve higher signal-to-noise ratio (SNR) or improved resolution by signal processing^[1].

Alamouti space-time coding scheme is commonly used in wireless communication area to decrease the probability of bit error. For MIMO SAR, we introduce Alamouti space-time code in transmitted waveform design to increase system SNR^[2]. Orthogonal signals are transmitted from the two antennas, and received signals can be decoded to acquire additional 6dB gain by Alamouti decoding matrix. OFDM-LFM is a group of orthogonal waveforms which has the same frequency slope but different center frequency. We select OFDM-LFM as transmitted signals to decrease interference of transmitted channels and improve range resolution of SAR image^[3].

In this paper, we employ Alamouti space-time code and OFDM-LFM waveform design to form a new MIMO SAR system. There are $2n$ transmitters in the system and the transmitted signals are orthogonally designed which have the same bandwidth and increasing center frequency. Every two transmitters and a receiver are designed as a group and Alamouti space-time encoding and decoding scheme is applied in every group. The simulation results prove that the new MIMO system can enhance system SNR and significantly improve range resolution of SAR image.

2. ALAMOUTI SPACE-TIME CODING SCHEME

The Alamouti code which is usually applied in mobile communication systems can be generalized as an orthogonal space-time code based on two transmitters. A generic Alamouti scheme is illustrated in Figure 1.

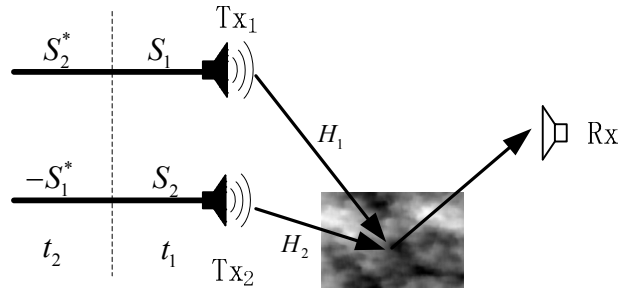


Figure 1. Generic diagram of Alamouti scheme

At a given period t_1 , two orthogonal signals S_1, S_2 transmits from antenna Tx_1 and Tx_2 , and complex conjugated singal $S_2^*, -S_1^*$ transmits at the next period t_2 . The channel influence of Tx_1 and Tx_2 denote by H_1 and H_2 . The symbol block \mathbf{S} and the channel vector \mathbf{H} are given by

$$\mathbf{S} = \begin{bmatrix} S_1 & S_2 \\ S_2^* & -S_1^* \end{bmatrix}, \quad \mathbf{H} = \begin{bmatrix} H_1 \\ H_2 \end{bmatrix} \quad (1)$$

The received signal at time t_1 and t_2 can be described by

$$\begin{aligned} Rx_1 &= H_1 S_1 + H_2 S_2 + n_1 \\ Rx_2 &= H_1 S_2^* - H_2 S_1^* + n_2 \end{aligned} \quad (2)$$

H_1, H_2 denotes the individual channel response, S_1, S_2 is the transmitted signal, and n_1, n_2 represents random complex additive white Gaussian noise.

The received signals also can be given as matrix form by

$$\mathbf{R}\mathbf{x} = \begin{bmatrix} Rx_1 \\ Rx_2 \end{bmatrix} = \begin{bmatrix} H_1 S_1 + H_2 S_2 \\ H_1 S_2^* - H_2 S_1^* \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} = \mathbf{H}\mathbf{S} + \mathbf{n} \quad (3)$$

In wireless communication system, transmitted code is recovered from received signal based on the modulation scheme such as BPSK or QPSK. But in radar system, it is needless to recover transmitted signal, we have priori knowledge about signal waveform matrix \mathbf{S} and \mathbf{S}^H . The Alamouti decoding can be directly implemented by multiplying \mathbf{S}^H with $\mathbf{R}\mathbf{x}$ signal.

$$\mathbf{R} = \mathbf{R}\mathbf{x}\mathbf{S}^H = (\mathbf{H}\mathbf{S} + \mathbf{n})\mathbf{S}^H = \mathbf{H}\|\mathbf{S}\|_F^2 + \mathbf{n} = \begin{bmatrix} H_1(|S_1|^2 + |S_2|^2) \\ H_2(|S_1|^2 + |S_2|^2) \end{bmatrix} + \mathbf{n} \quad (4)$$

\mathbf{S}^H is Hermitian transpose of matrix \mathbf{S} , and $\|\mathbf{S}\|_F^2$ denotes squared Frobenius nourn of matrix \mathbf{S} . If S_1, S_2 have the same power, which means $|S_1|^2 = |S_2|^2$, the Alamouti decoder can address additional gain of 6dB compared with conventional Single-Input Single-Output (SISO) SAR system^[4]. It is noticed that signal \mathbf{S} and \mathbf{S}^H are representations in frequency domain and the range compression has been accomplished in the step of Alamouti decoding. The simulation result of Alamouti scheme is shown in Figure 2, S_1, S_2 are linear frequency modulated (LFM) signal with 10dB white noise. Compared with conventional matched filtering, the magnitude of Alamouti decoding result has additional gain of 6dB.

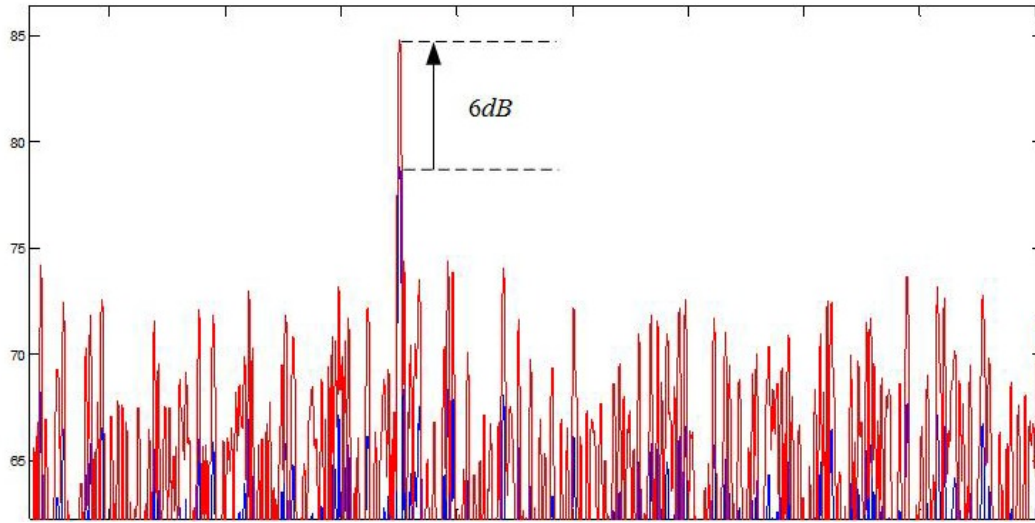


Figure 2. Comparison of range compression result using Alamouti scheme and conventional matched filtering.

3. OFDM-LFM WAVEFORM

OFDM-LFM is composed of a group of linearly frequency modulated subpulses which have equal chirp rate and different center frequency. OFDM-LFM waveform can be represented by

$$s(t) = \sum_{i=0}^{N-1} u(t) \exp(j2\pi f_i t) \quad (5)$$

$$u(t) = \exp(jK\pi t^2)$$

Where $u(t)$ is chirp subpulse, f_i is the center frequency of subpulse i and $f_i = f_0 + i\Delta f$. f_0 is starting frequency of subpulses, Δf is step frequency. K is chirp rate of every subpulse and $K = B/T_p$, B is bandwidth of subpulse, T_p is subpulse width^[5].

Because of the requirement of orthogonality between each subpulse, it should be satisfied with

$$\int_0^{T_p} s_m(t) s_n^*(t) dt = \begin{cases} C_m & m = n \\ 0 & m \neq n \end{cases} \quad (6)$$

Where $*$ denotes a complex conjugation operator and C_m denotes a nonzero constant. To reach this aim, any two subpulses cannot be overlapped in frequency domain, which can be expressed as:

$$B \geq \Delta f \quad (7)$$

High resolution radar imaging with OFDM-LFM can be achieved by frequency domain synthesis method based on match filtering algorithm. The subpulse i and the received signal can be described as:

$$s_i(t) = \exp(j2\pi f_i t + jK\pi t^2) \quad -T_p/2 \leq t \leq T_p/2 \quad (8)$$

$$r_i(t) = g_i(t) * s_i(t) \quad (9)$$

Where $g_i(t)$ is the reflection function of targets for subpulse i .

After down conversion and Fourier transform, expression (9) is transformed to

$$R_i(\omega - \omega_i) = G_i(\omega - \omega_i) \cdot S_i(\omega - \omega_i) \quad (10)$$

Where $\omega_i = 2\pi f_i$.

Match filtering in frequency domain can be expressed by:

$$G_i(\omega - \omega_i) = R_i(\omega - \omega_i) \cdot S_i^*(\omega - \omega_i) \quad (11)$$

Spectrum synthesis means the superposition of all reflection function $G_i(\omega)$ in frequency domain, which can be represented by

$$G(\omega) = \sum_{i=1}^{N-1} G_i(\omega - \omega_i + (i-1)\Delta\omega) \quad (12)$$

At last, high resolution radar imaging is obtained by inverse Fourier transform.

$$g(t) = IFFT[G(\omega)] \quad (13)$$

The results of OFLM-LFM simulation is shown in Figure 3 and simulation parameters are listed in Table 1. In Figure 3, we can see that main lobe width decreases gradually with the increase of the number of subpulse, which means the improvement of range resolution.

Table 1. OFLM-LFM simulation parameters.

Parameter	Value
Bandwidth of subpulse B	100MHz
Subpulse width T_p	10us
Step frequency Δf	100MHz
Number of subpulses N	1,2,4

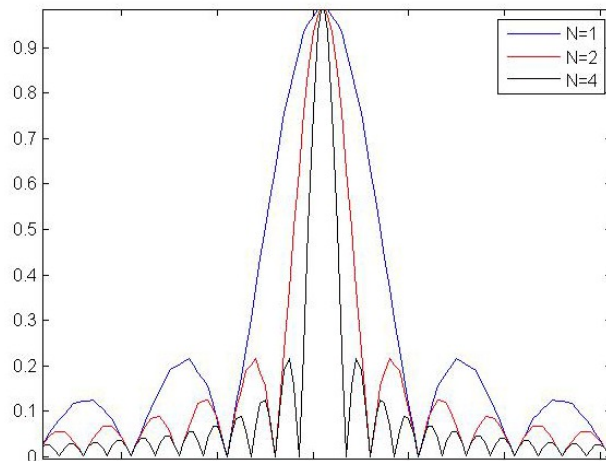


Figure 3. OFLM-LFM simulation result with different number of subpulses.

4. THE NEW MIMO SAR SYSTEM SIMULATION

In this section, the new MIMO SAR model is discussed and the proposed processing is demonstrated by simulations. MIMO radar system model is shown in Figure 4.

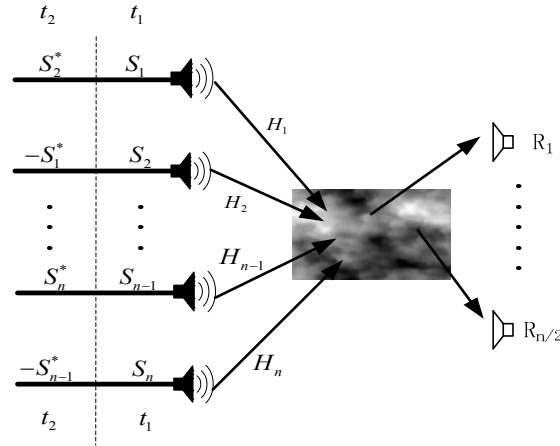


Figure 4. MIMO SAR system model

$S_1, S_2 \dots S_n$ is OFDM-LFM waveform which has the same bandwidth but different center frequency. $S_1^*, S_2^* \dots S_n^*$ is complex conjugated of signal $S_1, S_2 \dots S_n$. $S_1, S_2 \dots S_{n-1}, S_n$ is transmitted at time t_1 , and $S_2^*, -S_1^* \dots S_n^*, -S_{n-1}^*$ is transmitted at time t_2 . $R_1, R_2 \dots R_{n/2}$ is receiver, every two transmitters and a receiver are designed as a group.

Because $S_1, S_2 \dots S_n$ is orthogonal, Alamouti space-time encoding and decoding scheme can be applied in every group. The procedure of signal processing for the new MIMO SAR system is shown in Figure 5. Firstly, received data should be decoded by Alamouti decoding matrix. It is noticed that Alamouti decoding scheme is implemented in frequency-domain and the range compression has been accomplished in this step. Secondly, all of received data after Alamouti decoding should be realigned based on the center frequency of received signals. Thirdly, Inverse fast Fourier transform (IFFT) should be implemented to achieve higher range resolution. Finally, SAR image is generated through matched filter in the azimuth direction.

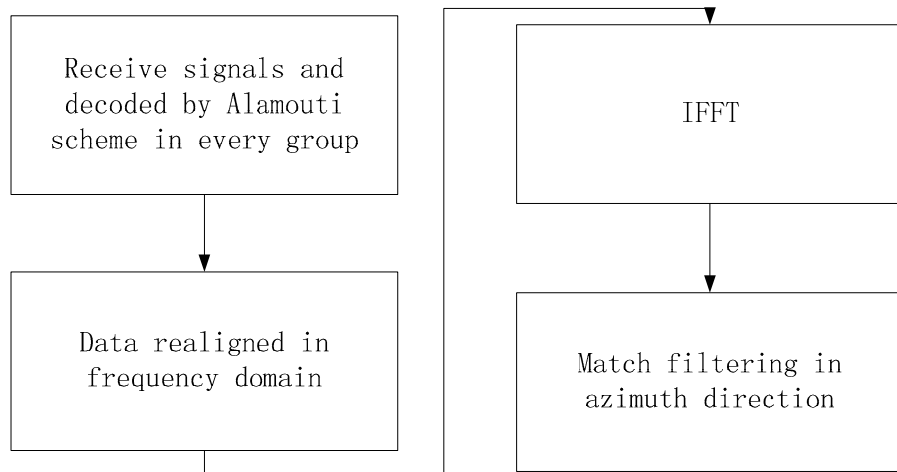
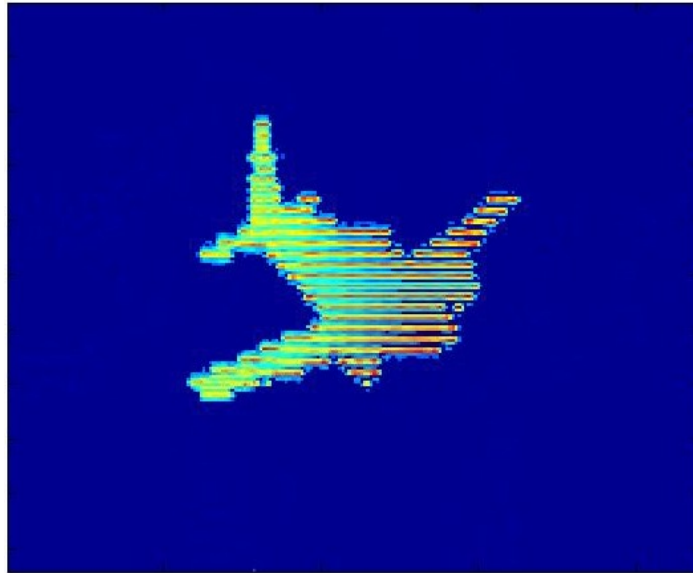
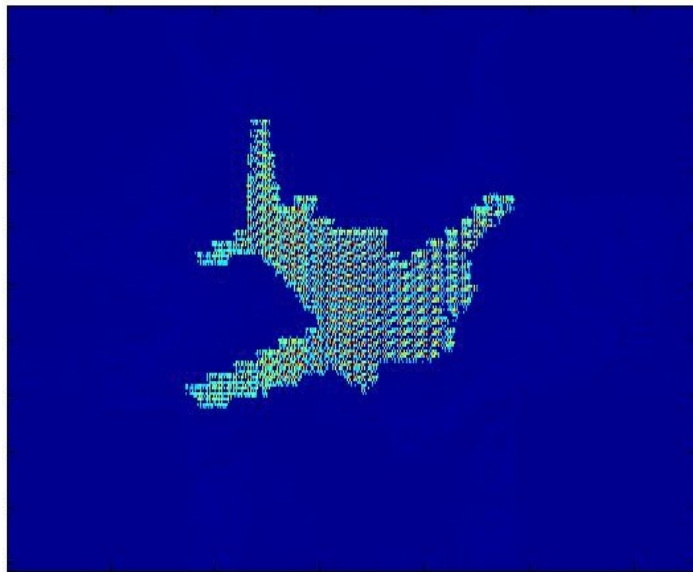


Figure 5. Flow diagram of signal processing for MIMO SAR system

The simulation result of an airplane model is shown in Figure 6. Figure 6(a) is SAR image generated by conventional SISO SAR system. Figure 6(b) is SAR image of new MIMO system with 4 transmitters and 2 receivers. Compared with Figure 6(a), Figure 6(b) has higher SNR and obvious improvement in range resolution.



(a) Conventional SISO SAR simulation result.



(b) New MIMO SAR system simulation result with 4 transmitters and 2 receivers.

Figure 6. Conventional SISO SAR and new MIMO SAR system simulation result

5. CONCLUSION

An innovative concept of MIMO SAR is proposed in this paper. The new MIMO SAR system is implemented by using Alamouti space-time coding scheme and OFDM-LFM theory. Alamouti scheme is employed at two separated transmitters and provides 6dB additional power gain in ideal. High range resolution can be obtained by OFDM-LFM waveform design and spectrum synthesis process. The simulation results indicate that the new MIMO system can enhance receive SNR and range resolution of SAR image. Because Alamouti scheme and OFDM-LFM waveform design can only improve the performance in range bin, our further work will be focused on high resolution application using Alamouti scheme and MIMO radar concept in azimuth direction.

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